

The University of Chicago

THE LONG LAKE DIORITE
AND ASSOCIATED ROCKS, SUDBURY
DISTRICT, ONTARIO

A PART OF A DISSERTATION SUBMITTED
TO THE FACULTY OF THE DIVISION OF THE
PHYSICAL SCIENCES IN CANDIDACY FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY

1932

By
BRUCE CLARK FREEMAN

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THE LONG LAKE DIORITE AND ASSOCIATED ROCKS, SUDBURY DISTRICT, ONTARIO¹

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ABSTRACT

The igneous petrology of an area near the Long Lake gold mine, Sudbury district, Ontario, is described. The area lies at the contact of a region of folded sediments and one of granite-gneiss. Two rock types, Keweenawan diabase and Long Lake diorite, resulted from the injection of basic magma into the sediments. Later a large granitic batholith invaded the region. Reaction between the magma and the quartz-rich sediments is postulated to account for a border phase of very quartz-rich tonalite. The Long Lake diorite grades into a more acidic phase and this phase is explained as due to emanations from the batholith affecting the diorite and adding silica and soda.

INTRODUCTION

LOCATION

The area described lies between Lat. $46^{\circ}15'$ and $46^{\circ}20'$ and Long. $85^{\circ}05'$ and $85^{\circ}15'$, just north of the Panache area mapped by Quirke and Collins. It is only about 15 miles southwest of Sudbury in a direct line, but is quite difficult of access, owing to the rough nature of the topography. The area is near the southern border of the Canadian shield between a region of folded sediments and one of granite and gneiss.

STRATIGRAPHY

Collins² has noted that the rock formations in the area north of Lake Huron are grouped into four main structural elements:

The four elements are, from oldest to youngest:

1. A pre-Huronian floor or basement upon which the other groups rest.
2. A thick succession of Huronian sedimentary formations and associated igneous formations lying in profound angular unconformity upon the pre-Huronian—or in the case of the intrusives—breaking through.

¹ Published with the permission of the Director of the Geological Survey of Canada. The writer wishes to acknowledge his indebtedness to Dr. T. T. Quirke, of the Geological Survey of Canada, and to Professors E. S. Bastin and A. Johannsen, of the University of Chicago.

² W. H. Collins, "North Shore of Lake Huron," *Can. Geol. Surv. Mem.* 143 (1925), p. 15.

3. Palaeozoic formations, which rest in quite as profound angular unconformity upon the Huronian.
4. Unconsolidated Pleistocene glacial materials and lake beds, which lie unconformably upon all the older groups.

In the area under consideration only elements 2 and 4 are found, and of these two, the latter has no special significance for the purposes of this report.

The pre-Cambrian rocks may be arranged as in the accompanying list, with the youngest at the top.

4. Scattered dikes of fresh olivine diabase, apparently much younger than any of the other pre-Cambrian formations.
3. Killarnean batholithic intrusions.
2. Sills and dikes of diabase, quartz-diabase, diorite, and tonalite, probably of Keweenawan age.

IGNEOUS CONTACT

1. Bruce series, consisting of

- | | |
|-----------------------|-------------------------|
| a) Serpent quartzite | c) Bruce conglomerate |
| b) Espanola formation | d) Mississagi formation |

BRUCE SERIES

All of the sediments of the region belong to the Bruce series, Lower Huronian in age, and the other three groups of rocks are igneous and intrusive into the sedimentary formations. All members of the Bruce series are represented, but no other Huronian formations have been spared by erosion.

The Bruce series is, however, so metamorphosed that its original sedimentary character is largely masked. *Memoirs 102, 143, and 160* of the Geological Survey of Canada contain excellent descriptions of these rocks from the typical areas, and describe the metamorphic changes produced in them. The sediments are predominantly impure feldspathic quartzites and graywackes.

KEWEENAWAN DIABASE

The diabasic rocks, intruding the Huronian and pre-Huronian formations as dikes and sills, have been described in many reports

and papers. The most complete accounts appear in memoirs of the Geological Survey of Canada, of which five are listed below.³ Rock of this type is widespread in the region north of Lake Huron, occurring as far north as the Cobalt and Gowganda areas, and is perhaps correlative with the Keweenawan intrusives of the Lake Superior region.

The diabase is typically a massive, quite fresh-appearing, dark-greenish-gray to black rock, with size of grain varying with the thickness of the intrusive mass. Small dikes are dense, black, and basalt-like, and at the other extreme thick sills are gabbro-like (6 mm. minerals), although the usual grain in most sills is medium (about 2 mm.). Within the sills the diabase also varies in appearance and mineralogical composition, owing to assimilative and differentiative processes in the more slowly cooling magma. There are patches of much coarser material, a yard or so across, that rarely show definite boundaries against the more usual phases. Infrequent dikes of a red-to-white aplitic differentiate cut the diabase, and "red rock" occurs in indefinite patches of dull-reddish material, which owes its color to the fact that the feldspar is red instead of light gray in reflected light.

Fine-grained fresh phases have a diabasic texture and are composed of intermediate labradorite and augite in about equal proportions, with a little quartz in the angular interstices between the chief minerals and with accessory titaniferous magnetite and apatite, and a very little biotite, pyrite, and chalcopyrite. The pyroxene is very often altered to green hornblende.

The coarser phases show more mineralogic variability. The plagioclase is more variable, ranging from bytownite in some places to andesine in others. A micrographic intergrowth of quartz and andesine is present in amounts over 10 per cent in some places. The most acidic plagioclase outside the intergrowth is optically identical with that in the micrographic intergrowth. When some titanite and biotite are present in coarse diabase, the plagioclase is usually red in re-

³ *Mem.* 33 (1913), pp. 59-63 and Pl. III, Figs. 3, 4, and 15; *Mem.* 95 (1917), pp. 84-101 and Pl. VII B, VIII A and B, X A and B; *Mem.* 102 (1917), pp. 49-55; *Mem.* 143 (1925), pp. 77-82 and Pl. XIV A and B; *Mem.* 160 (1930), pp. 29-30, 37, and 99-101. The most extended discussion is given in *Mem.* 33, and the discussions in the later memoirs are, in large part, summaries of the original one.

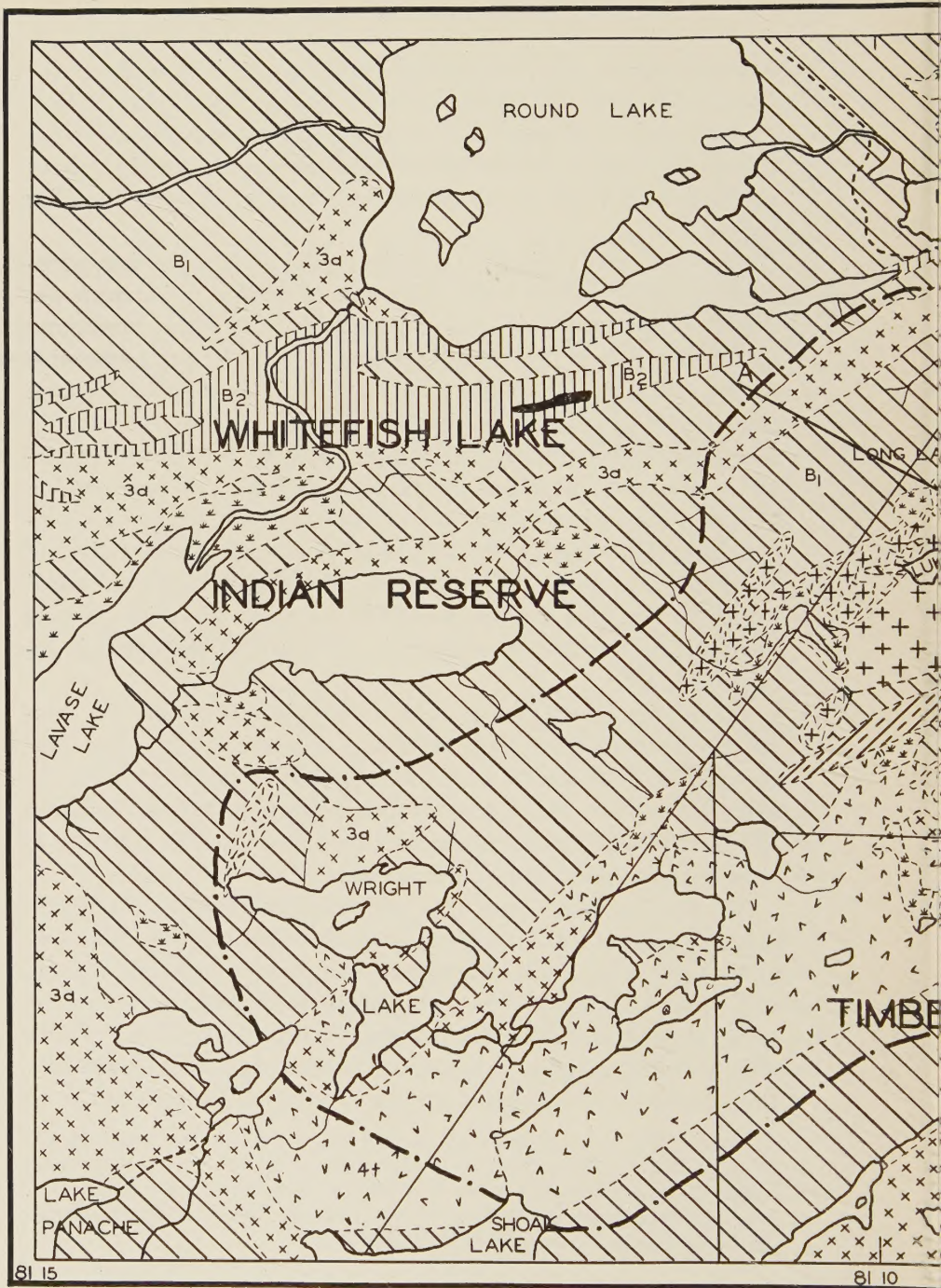
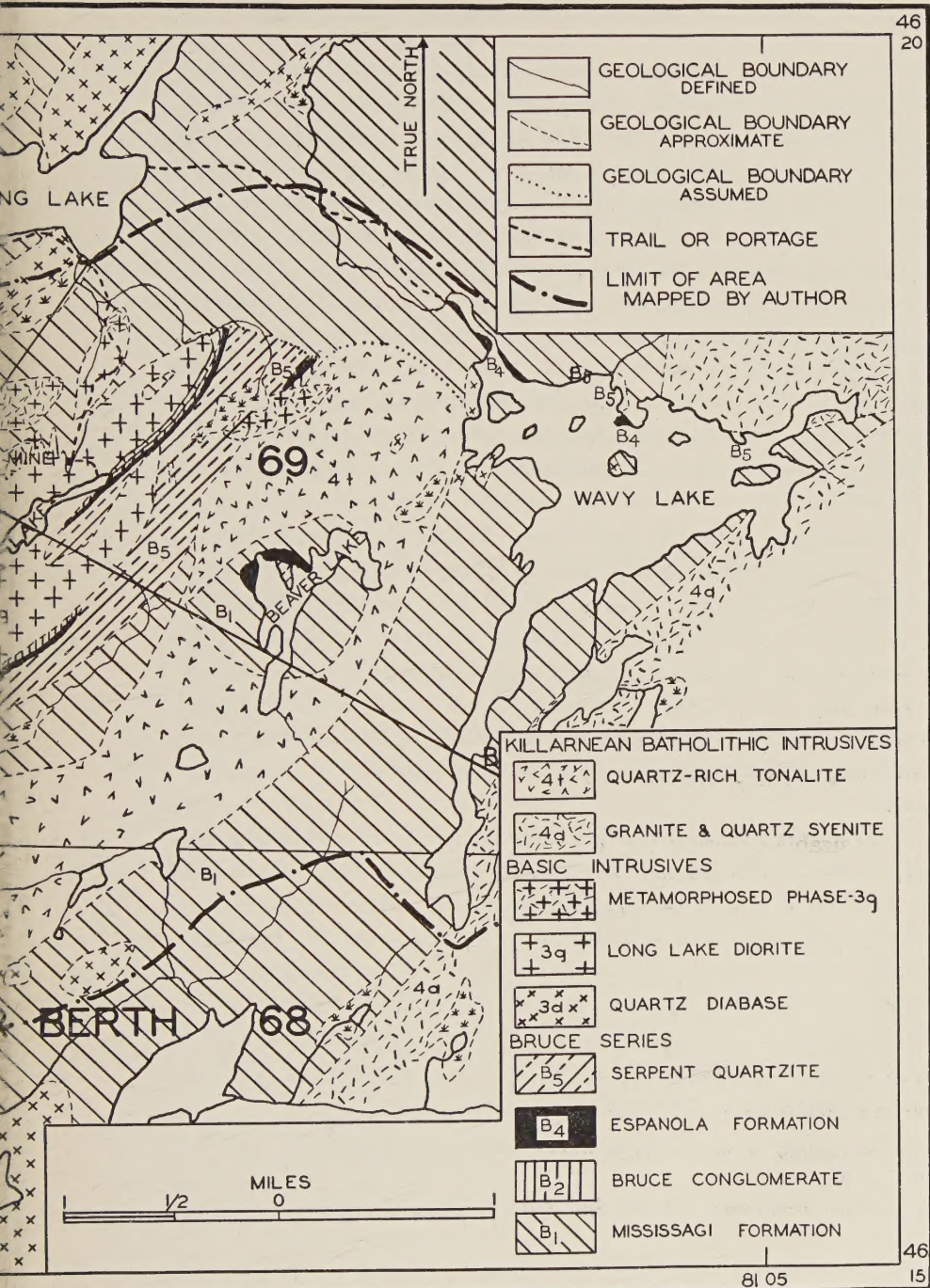


FIG. 1.—Geological map of the ar



round the Long Lake Gold mine

flected light. This phase, composed of acidic plagioclase, biotite, micrographic intergrowth, and titanite, with some magnetite, is called "red rock" when it occurs in fairly large masses; however, it does occur in all proportions mixed with diabase, varying from numerous small red spots up to sizable masses that contain little diabase. Aplite differs from "red rock" in that it has a much more acidic plagioclase, some of which is practically pure albite, and it contains no magnetite. The texture of both "red rock" and aplite is granitic.

Collins interprets the association of the three above-described rock types, namely, coarse diabase, "red rock," and aplite, as due to crystallization differentiation in the magma, although he does not exclude the possibility that assimilation of sediments has affected the course of differentiation. He has shown that some assimilation has taken place.⁴

Metamorphic effects of the diabase.—Where the diabase has invaded the older formations without breaking off and engulfing fragments its metamorphic effects are not very marked. Huronian quartzite was rendered glassy and more perfectly recrystallized for a short distance from the contacts, varying from a few inches to several feet. Graywacke is bleached for a distance of about 1 yard from the diabase, is filled with black spots of chlorite, and becomes essentially a recrystallized aggregate of quartz and acidic plagioclase.

In all sizable masses of diabase there are occasional lighter patches very much coarser grained than the surrounding rock. In some of these there is a core of corroded quartzite. The boundaries are usually indefinite. The distribution is variable, but in places the patches amount to 10 per cent of the total. Collins has shown that these lighter patches represent inclusions partly assimilated by the diabase magma.⁵ It is quite possible that the assimilation of such a large amount of sedimentary material had an appreciable effect on the course of differentiation of the magma.

⁴ "The Geology of the Gowganda Mining Division," *Can. Geol. Surv. Mem.* 33 (1913), p. 80.

⁵ "Onaping Map-Area," *Can. Geol. Surv. Mem.* 95 (1917), pp. 61-62.

OLIVINE DIABASE

Olivine diabase is very widespread in the region, always occurring as dikes, most of them small, but some fully 100 feet wide. Only a few occur in this area, and they are so small that they are not shown on the accompanying map. M. B. Baker, however, has shown four on his map of the vicinity of the Long Lake gold mine.⁶ Olivine diabase is the youngest rock in the region, if the Pleistocene deposits are excepted, and cuts all the other rocks. It is separated from the quartz diabase by the episode of the intrusion of the Killarney granite.⁷

Megascopically the rock resembles quartz diabase, and can be separated from it in the field only with difficulty. Olivine diabase, however, appears fresher, with brighter, more glassy feldspar. It is a fresh, black rock consisting of labradorite, olivine, and magnetite

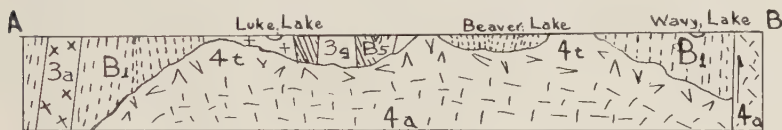


FIG. 1a.—Structure section along line A-B on map

crystals in a base of purplish-brown, titaniferous augite. The rock consists of approximately 60 per cent zoned labradorite, 30 per cent augite, 10 per cent olivine, and accessory magnetite, biotite, and apatite. The texture is intergranular, a variety of ophitic texture in which the interstitial augite is in grains and not in large crystals.

THE LONG LAKE DIORITE

CHARACTER OF INTRUSION

The intrusive mass of the Long Lake diorite outcrops in an irregular form. There are five masses: a larger, irregular central mass with four smaller lenticular masses around it. Since the total length is 3 miles, and the greatest width $\frac{3}{4}$ mile, it is, therefore, about four times longer than it is wide. It appears to conform generally to the

⁶ "Long Lake Gold Mine, Sudbury District," *Ont. Bur. Mines, Ann. Rept.*, Vol. XXVI (1917), Map 26e.

⁷ Collins, "North Shore of Lake Huron," *Can. Geol. Surv. Mem.* 143, p. 84.

strikes and dips of the adjacent sedimentary formations, although the contacts are transgressive to a limited degree in some places. The rocks of the Bruce series are nearly vertical, forming a closely appressed syncline. The diorite intrusive is mainly in the northwest limb of the syncline, with the exception of the mass 1 mile north of Beaver Lake which is in the other limb. Apparently the injection followed the folding of the sediments and the diorite pushed the rocks aside to make room for itself.

Brecciated contacts are widespread, but are particularly well shown near the mine road about $\frac{1}{4}$ mile south of Long Lake. Here the Mississagi quartzite is brecciated and tongues of diorite fill in around the angular blocks. Elongated, altered quartzite inclusions occur well within the diorite.

The diorite outcrops in ridges resembling a series of parallel dikes, since erosion has been more rapid along certain planes of weakness. These dikelike outcrops have practically vertical walls, 5-20 feet high, and variable widths extending about 300 feet. The shores of Luke Lake, which lies almost in the center of the diorite mass, furnish excellent outcrops.

TYPICAL PHASE

The usual rock type, and the one considered typical, is megascopically a fine- to medium-grained, dark-gray rock composed mainly of feldspar and hornblende in about equal amounts. It closely resembles a diabase, and many outcrops were called diabase in the field because of this resemblance.

The texture is hypautomorphic-granular and subophitic, with a slight tendency to parallelism of the hornblende and feldspar individuals. Both minerals are lathlike in habit, as is particularly well shown in some hornblende individuals which have a length as much as 7 mm. in specimens otherwise only millimeter grained (Fig. 2.)

Plagioclase and hornblende, with plagioclase only slightly in excess, make up nearly all the rock. A very small amount of quartz is present as well as 1 or 2 per cent of biotite. Titaniferous magnetite and apatite are constant accessories. As secondary minerals clinozoisite is always present and flakes of white mica are commonly found as alteration products of plagioclase; a little chlorite is ordinarily secondary after hornblende.

The plagioclase in the fine-grained rock type is andesine-labradorite. In one case zoned crystals were found with centers as basic as $\text{Ab}_{30}\text{An}_{70}$, but this is unusual. The composition varies from $\text{Ab}_{30}\text{An}_{70}$ to $\text{Ab}_{60}\text{An}_{40}$, but the usual composition is between $\text{Ab}_{55}\text{An}_{45}$ and $\text{Ab}_{50}\text{An}_{50}$.

The more basic centers of the plagioclases are generally somewhat altered. Clinzoisite is developed in them to a notable extent and there are flakes of white mica. In only a few cases, however, is the entire crystal altered to a saussuritic mat of interlocking fibers.

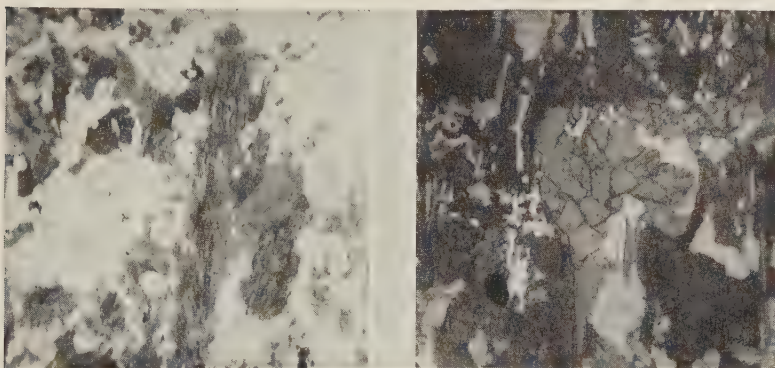


FIG. 2

FIG. 3

FIG. 2.—Typical Long Lake diorite. Ordinary light. $\times 10$. The dark mineral is hornblende.

FIG. 3.—Secondary garnet in poikilitic hornblende with quartz chadacrysts. Ordinary light. $\times 30$.

Often the center of the crystal is unaltered, but an intermediate zone is altered. The rim in almost all cases is remarkably clear and fresh appearing, and is often untwinned. The plagioclase is in crystals about twice as long as wide, but there is practically a complete absence of automorphic boundaries. It is quite fresh, but albite twinning usually is not well developed.

The amphibole is the blue-green variety of common hornblende ordinarily found as a primary mineral in igneous rocks. The individuals are in lath-shaped crystals; none of them has the terminal faces developed and most of them are ragged and indented along the sides (Fig. 2). When basal sections are shown, however, a good

many crystal faces can be seen with the characteristic angles. If this mineral were secondary after pyroxene such outlines would not be present unless the whole rock has been recrystallized, and there is no evidence that this has occurred. In practically all cases hornblende laths dominate the texture, both microscopically and megascopically. In most hornblende crystals there are black specks and dots of magnetite which are arranged in a roughly linear fashion and are more numerous in the centers of the crystals than near the edges. The larger crystals are cracked by minute cross-fractures. There are a few flakes of biotite within most crystals, and often a small amount in parallel intergrowth with the hornblende. Some alteration to chlorite is shown, but on the whole the hornblende is notably fresh. In a few cases pleochroic halos occur.

VARIATIONS

The diorite varies in appearance, owing to the local presence of rock types caused by differentiation in the cooling magma, possibly by assimilation, and by metamorphism by the later Killarney batholith. Five such variations are described.

1. *Coarse-grained patches*.—Coarse segregations are apparently due to slow crystallization. Two sets of specimens were taken across gradations from fine- to coarse-grained material. With increasing coarseness there was an increase in the amount of primary quartz and the hornblende crystals became more irregular in outline. These changes would be expected in the more slowly solidifying parts of a magma. Any excess of free silica would collect in the places where solidification was slowest and would crystallize last. The raggedness of the hornblende crystals is probably the result of reaction with the remaining magma, and the slower the crystallization the more time was available for reaction between the already crystallized hornblende and the liquid residue.

2. *Reddish dikes*.—At the small island in Luke Lake there is an outcrop of a red rock, and 300 feet west of the outlet on the north shore there are ramifying stringers of the same material, 4-14 inches wide, with sharply defined but irregular contacts, cutting the diorite. This rock type is a dull-reddish-gray, medium-grained (2 mm.), granular-textured rock that does not resemble any other rock in the

area, but agrees quite well with published descriptions of the "red rock" associated with the Keweenawan diabase.⁸ The rock at Luke Lake is composed of 82 per cent reddish-colored oligoclase ($\text{Ab}_{75}\text{An}_{25}$) 5 per cent quartz, 10 per cent biotite, with hornblende, apatite, titaniferous magnetite, and pyrite making up the remaining 3 per cent. Bowen thought that the red rock of the Gowganda area resulted from interaction at the contact, some of the sediments being assimilated by diabase magma to give a mixture that solidified with the textures of an igneous rock.⁹ Collins, however, concluded that red rock is a normal differentiate of the diabase magma that has not been affected by assimilation.¹⁰ Whatever the origin, the presence of this rock type suggests a relationship between the Long Lake diorite magma and the Keweenawan diabase magma.

3. *Metamorphosed phase*.—The metamorphosed phase is confined mainly to the peripheral parts of the intrusive. In the field the only constant accompaniment of alteration is the Killarney intrusives. One mass, $\frac{3}{4}$ mile north of Beaver Lake, lies partly within the large mass of Killarney tonalite stretching from Wavy Lake to Wright Lake. All of the rocks, diorite and Bruce sediments, northeast of Luke Lake are fairly riddled by small outcrops of very quartz-rich Killarney intrusives. These small quartz-rich tonalite masses, many of which are dikelike, would seem to indicate a very close approach of the Killarney batholith to the present surface. This close association of Killarney tonalite and altered diorite suggests a genetic connection, and the writer believes that the tonalite caused the metamorphism.

Within very short distances the metamorphosed rock varies notably in color, in texture, and in mineralogy. These variations range from little-altered diorite to a medium-grained rock, light gray, granular in texture, composed of plagioclase, biotite, and quartz, and resembling a dark-colored granite or a syenite in the field.

The constituents, as determined under the microscope, with their

⁸ Collins, *op. cit.*, *Mem.* 33, p. 63, and *op. cit.*, *Mem.* 95, pp. 92-94; N. L. Bowen, "Diabase and Granophyre of the Gowganda Lake District, Ontario," *Jour. Geol.*, Vol. XVIII (1910), pp. 658-74.

⁹ *Ibid.*, p. 673.

¹⁰ *Ibid.*, pp. 92-94.

approximate percentages are: oligoclase between $Ab_{70}An_{30}$ and $Ab_{80}An_{20}$, about 70 per cent; quartz, 10 per cent; biotite, 15 per cent; hornblende, 1 or 2 per cent; with garnet, titaniferous magnetite, and apatite as accessories. The main changes involved are: reduction in the amount of mafic constituents, especially hornblende; a marked increase in the sodic character of the plagioclase; the introduction of a notable amount of quartz; the presence of accessory garnet; and reduction in amount of titaniferous magnetite.

The garnet resembles grossularite and is probably an iron garnet. It is associated with the mafic constituents more closely than with others. There is a suggestion that it may have pushed the hornblende aside in crystallizing (Fig. 3), and this, if true, means that it is present as metacrysts. Some of the biotite is developed as metacrysts and has replaced the original rock to make room for itself.

Quartz occurs as both a primary and a secondary constituent. Part of it is in small crystals among the other constituents as is the normal habit of primary quartz, but the larger part is present as small, rounded chadacrysts in the hornblende, which is very markedly poikilitic (Fig. 3). In extreme cases the hornblende, and, at times, biotite also, is shredded by introduced quartz to such an extent that only small remnants remain in large quartz aggregates. A small amount of quartz is also present as small irregular stringers in feldspar.

The foregoing indicates that the changes produced in the diorite as it was metamorphosed were: (1) the introduction of quartz into the rock, principally into the hornblende as chadacrysts, producing a marked poikilitic habit in the hornblende; (2) the introduction of soda, causing the plagioclase to become more acidic (andesine-labradorite became oligoclase); (3) the reduction in amount of the dark constituents, owing to the combined influence of the silica and soda; (4) the reorganization of hornblende into biotite; (5) the formation of garnet—probably owing to the influence of the iron in the magnetite.

Any one of three possible processes, or combinations of them, might account for these changes:

a) Crystallization differentiation.—The changes described could be produced by the settling of more basic crystals in the liquid magma during the course of normal crystallization differentiation.

b) Assimilation of sedimentary rocks.—The Huronian quartzite might react with the magma so as to add the soda and quartz.

Both of these processes would be operative while the magma was still liquid.

c) Metamorphism by emanations from the quartz-rich tonalite.—The altered rock is in very close association with outcrops of tonalite, as noted on page 33. The appearance of this rock type differs from that of material known to have been assimilated, as described on the following page. The presence of rounded blebs of introduced quartz in the mafic constituents is very strong evidence that the changes occurred after solidification of the magma, and metamorphism by emanations is the only one of the three processes that would be operative in the solid state. For these reasons the writer believes that the rock type under consideration is an altered phase of the diorite, metamorphosed by the tonalite.

4. *Patches*.—Patches characterized by extremely long and thin hornblende laths and associated with the metamorphosed phase show a decided orientation of the minerals. The hornblende and biotite are extended in a plane roughly parallel to the present surface. These minerals have a remarkable development in this plane and cause the outcrops to scale off in large thin layers, a yard or so across and only an inch or two thick. This layered character could have been brought about only by crystallization under directed pressure, and therefore in a state approaching the solid, i.e., by piezo-crystallization. The writer concludes that the formation of the hornblende and biotite in these variants took place under a directed pressure caused by the presence of the Killarney batholith a short distance below. The patches, therefore, are also considered a metamorphosed phase of the Long Lake diorite and were caused by the intrusion of the Killarney batholith.

5. *Metamorphism and assimilation by the diorite*.—There are numerous xenoliths within the intrusive, four of which are large enough to be shown on the map. These inclusions are altered and recrystallized to a large extent and the smaller ones are completely changed. One example, $\frac{1}{8}$ mile west of the head of Luke Lake and 100 feet south of the large xenolith of Mississagi formation, is an altered patch 10 by 4 feet with a fairly definite boundary against the diorite.

Within this patch hornblende, plagioclase, and quartz are in a confused intergrowth. Quartz weathers out into little masses like runic characters, and the hornblende metacrysts are an inch or more in length. Thin sections of this rock show that the minerals have interlocking boundaries.

In another place, a quarter of a mile south of the one just described, a somewhat larger mass of quite light-colored, feldspar-rich material lies within diorite. The light material is not homogeneous, but has variegated bands of much darker material which are rich in hornblende. Hornblende is present as metacrysts lying in a base of subparallel, andesine laths and quartz crystals and enclosing some of these minerals. Collins has described similar cases in the Keweenaw diabase from the Gowganda area,¹¹ and from the north shore of Lake Huron.¹²

The most striking product of metamorphism, however, is a spotted rock composed of white feldspar with irregular, rounded, hornblende metacrysts about 1 cm. in size. The hornblende weathers into relief to produce a rough surface. In thin section the rock is seen to be composed mainly of hornblende and labradorite in proportions about 1 to 2, although the proportions vary noticeably. The feldspar crystals wind about and lie within the hornblende metacrysts.

COMPARISON OF DIORITE AND DIABASE

On comparing the Keweenaw diabase and the Long Lake diorite, certain strong similarities between them are evident: (1) in age both belong to the time between the deposition of the Huronian sedimentary formations and the intrusion of the Killarney granite; (2) both contain "red rock" although the amount in the diorite is relatively small; (3) both contain coarse segregations; (4) the chemical composition of the diorite, as computed from Rosiwal's analyses, agrees closely with published analyses of the diabase; (5) the two rock types are very similar in hand specimens, and therefore are distinguishable in the field only with extreme difficulty.

On the other hand, differences exist which are great enough to cause Collins to regard them as separate intrusions:¹³ (1) the chief

¹¹ *Can. Geol. Surv. Mem.* 95, pp. 61-62.

¹² *Ibid.*, *Mem.* 143, p. 80.

¹³ Personal communication, April 1, 1932.

mafic constituent is primary hornblende in the diorite and pyroxene (which is largely amphibolized) in the diabase; (2) the plagioclase is somewhat more sodic in the diorite; (3) quartz is smaller in amount in the diorite, (4) micrographic intergrowth is absent in the diorite; (5) the diorite grades into a tonalitic phase, which the writer regards as a metamorphosed phase of the diorite.

The writer believes that the magmas of the diorite and diabase came from a common source and that the differences are due (1) to a different course of differentiation, and (2) to the effect of the Killarney batholithic intrusives on the diorite, as will be considered more fully later in the report.

KILLARNEY BATHOLITHIC INTRUSIVES

DISTRIBUTION

Killarney batholithic intrusives are widespread in the area and are much more pervasive than the diorite and diabase. The granite shown at the eastern side of the area is part of a large mass that extends with some interruptions to Killarney on Georgian Bay.¹⁴ A mass of very quartz-rich tonalite extends from Wavy Lake to Wright Lake. These two rock types are shown on the accompanying map, but an enormous number of pale-gray, quartz-rich tonalite dikes, similar in appearance and mineralogical composition to the large mass, cut all the other formations without regard to their structure and are too small to be shown on a map of this scale.

QUARTZ-RICH TONALITE

The tonalite is a pale-gray, medium-grained (3-4 mm.), equigranular rock composed mainly of quartz and oligoclase ($Ab_{85}An_{15}$) in about equal proportions, with a little potash feldspar, mainly microcline, a few per cent of biotite, and accessory titaniferous magnetite, and apatite.

Numerous dikes and small masses of similar rock surrounding the quartz-rich tonalite mass make the location of the contact with the sediments a matter of individual judgment. East of Wright Lake the Mississagi formation is severely metamorphosed and intruded by a host of small offshoots from the batholith. The diabase mass north of Wright Lake is also cut by numerous dikes and is altered to rock in

¹⁴ *Op. cit.*, *Mem. 160*, Map 220A, Panache Sheet.

which the hornblende laths are prominent and which resembles very strongly the Long Lake diorite. As mentioned on page 33, there is also a very large number of small intrusive masses northeast of Luke Lake.

The dikes are irregular in shape. Some are wall shaped, others resemble lenses, or are irregularly shaped. The quartz grains are especially resistant to weathering and protrude about $\frac{1}{8}$ inch above the other constituents, thus forming a rough surface. These grains when crushed under foot make a peculiar crunching, grinding noise. This peculiarity of weathering makes it easy to distinguish in the field between quartz-rich and quartz-poor dikes, both of which are present. These dikes are fresh, unsheared, not displaced, and apparently are the last manifestations of the batholithic intrusion. Their contact effects on the sediments seem to be almost nil. They show no chilling or difference of grain within themselves. Even little dikes, 6 inches wide, are medium grained from edge to edge.

The chief difference between the dikes and the large masses of tonalite is the different nature of the contacts. Almost everywhere large masses pass into quartzite by a complete gradation. On a traverse from the southwest end of Luke Lake southeast to the small lake on the boundary between timber berths 68 and 69, patches of gray, quartz-rich, igneous-appearing rock were found in the Missisquoi quartzite $\frac{3}{4}$ mile from Luke Lake, about where the small stream enters the swamp. Farther along the traverse these patches became more and more numerous and larger, until at a distance of 1 mile from Luke Lake the igneous rock was in excess and sediments were contained in it. The outcrops were very numerous and sharp contacts especially were searched between bedded and cross-bedded feldspathic quartzite and the gray tonalite. Practically none was found; the bedding planes in the pinkish-gray quartzite faded out next the intrusive and the rock appeared gray, somewhat coarser grained, and with fresher minerals. The feldspar especially was gray, with bright cleavage faces 2 or 3 mm. across, whereas in the sedimentary rock it was dull reddish, without noticeable cleavage faces.

The conclusion seems unescapable that the large masses of tonalite either originated in place or else assimilated enough of the country rock after emplacement to produce the gradational contacts.

GRANITE

The granite is a coarse, reddish rock composed largely of phenocrysts of orthoclase, with 5-10 per cent quartz, some oligoclase-albite, and a little biotite.

On the north shore of Wavy Lake, at the contact between Huronian quartzite and granite, the quartzite is very much metamorphosed, highly sheared in a vertical plane, and altered into a complex of highly schistose muscovite rock and vitreous translucent quartz. The phenocrysts of the granite are aligned and also sheared internally, but the base is not noticeably affected. The granite appears to have been pushed into place, shearing internally, and shearing against the quartzite when it was essentially solid. Numerous quartzite xenoliths are within the granite and these appear to be in parallel orientation with the sediments outside. No twisting or rotation of the xenoliths occurred, in spite of the shearing of them and of the granite, probably because the granite came up vertically and merely tore off slivers of quartzite which it carried up bodily with it.

The line of contact between the main Killarney batholith and the sediments was drawn near the east side of Wavy Lake. West of this line the rocks are prevailingly sediments cut by small, gray, granite dikes. East of this line the rocks are dominantly coarse, pink granite with minor but clearly sedimentary inclusions many of which are more or less completely granitized. This contact is a most important line of division and probably marks the position of a great dislocation. Presumably the area east of the contact was once covered by an upper tonalite differentiate and this in turn by Huronian sediments, and the area west of the line of contact is, by the same reasoning, underlain at depth by granite.

AGE RELATIONS OF THE IGNEOUS ROCKS

GRANITE

The pink granite is so typically Killarnean in aspect that there can be no doubt of its identity with the Killarney granite.

TONALITE AND GRANITE

Gray tonalite dikes are very numerous at the contact of granite and sediments. The prevalence of gradational contacts between the larger masses of tonalite and sediments has been noted above. The

composition of the sedimentary series is quite similar to a very quartz-rich, soda granite. Reaction between the magma of the Killarney granite and inclusions of the type of the impure quartzites of this area would produce a reaction product similar to the quartz-rich tonalite.¹⁵ The writer believes that the field relations are best explained by reaction between the granite magma and the sediments. The larger masses of tonalite originated, according to this view, approximately in the place that they now occupy, and the smaller dike-like masses were squeezed out of the larger masses during their solidification. The sediments had been sufficiently heated since the intrusion of the Long Lake diorite so that reaction between granite magma and sediments could take place and small dikes of tonalite could solidify without chilling. That the great batholiths of the Canadian shield had an enormous effect on the overlying rock has long been recognized. In 1921 J. Barrell said that it was probable that pervasive magmatic waters emanating from granite magmas had caused the regional alterations of the Keewatin lavas.¹⁶ The work of Quirke and Collins in the Area immediately south of this one also supports the contention of large-scale alteration by the processes of batholithic invasion. Indeed, they claim a very large amount of formation of igneous rock in place. They say:

In places where liquid masses were intruded from greater depths towards the upper part of the crust replacement was negligible, and sharp contacts . . . resulted. But at great depths . . . igneous intrusion was either antedated or usurped by enormous metasomatism, whereby the rocks were so profoundly altered, through soaking with magmatic emanations, that their composition and textures were notably altered.¹⁷

The writer believes that the tonalite originated under some such conditions and that it was emplaced quietly through processes of regional metasomatism and assimilation of the overlying sediments. The description of the changes in the Long Lake diorite to produce the metamorphosed phase is another record of the workings of these processes. The lack of definite contacts between the larger quartz-rich tonalite masses and the Huronian quartzites is also evidence of

¹⁵ Bowen, *op. cit.*

¹⁶ "Relations of Subjacent Igneous Invasion to Regional Metamorphism," *Amer. Jour. Sci.*, Vol. CCI (1921), p. 180.

¹⁷ *Can. Geol. Surv. Mem.* 160, p. 95.

the quiet invasion of country rock at considerable depth by an igneous rock. This quiet invasion is also evidenced by the shape and position of the metamorphosed mass of diorite lying partly within quartz-rich tonalite. Had the intrusion been violent there should be evidence of crosscutting by the igneous rock, so common in rocks intruded at slight depths.

TONALITE AND DIORITE

The Long Lake diorite has been assigned to the same period as the granite by most previous investigators,¹⁸ who appeared to consider it a basic marginal phase of the granite. Baker, however, states that it is cut by granite and is therefore somewhat earlier. A negative reason for not believing that the diorite and granite are intimately related in origin is the absence of basic borders about the granite elsewhere in the general district. The batholiths of Killarney age in the district are believed by Quirke and Collins to have originated about 6 miles below the surface, but even at that depth they find no trace of the source of any basic magma.¹⁹ If the other Killarney batholiths are not the result of differentiation from a basic magma, no reason exists to believe that this one is.

The writer found numerous localities where the diorite was cut by tonalite dikes. The mass of metamorphosed diorite lying partly within the tonalite northeast of Luke Lake is cut by numerous tonalite dikes and irregular offshoots. A very significant outcrop is found 200 feet south of the east end of this mass. Here Serpent quartzite is cut by two dikes, one of coarse tonalite, the other of fine diabasic appearing diorite, apparently coming from the large mass to the north. The tonalite is about 25 feet long, 2 feet wide at the east end, irregular in width, pinching and swelling, ending in a club-shaped widening at the west end, but about 3 feet wide on the average. It is coarse grained from edge to edge and shows absolutely no chilling at the borders. The diorite dike is 4 feet south of the tonalite dike and about parallel with it. It is 15 feet wide, is exposed for 35 feet, and appears to be coming from the large dioritic mass. It is fine grained

¹⁸ A. P. Coleman, "The Pre-Cambrian Rocks North of Lake Huron," *Ont. Bur. Mines Ann. Rept.*, Vol. XXII (1914), p. 219; M. B. Baker, *ibid.*, Vol. XXVI, Part I (1917); W. H. Collins, *Can. Geol. Surv. Mem.* 143, p. 121.

¹⁹ *Op. cit.*, *Mem.* 160, p. 98.

from edge to edge. The two dikes are not in contact so that their relative age is not absolutely definite. Neither is sheared. In thin section the small tonalite dike resembles sections from large masses of the same rock. Since the dioritic dike has andesine feldspar, 10 per cent quartz, no hornblende, and 20 per cent biotite, as well as 2 per cent garnet, it is, therefore, the metamorphosed phase of the diorite.

The diorite must have preceded the tonalite by a period sufficient to allow the solidification of the dike in relatively cool country rock. The tonalite must have been intruded into heated rocks, or such a small mass as the one under consideration would have been chilled. After the intrusion of the diorite and the solidification of dikes from the main mass the sediments into which it had been injected were heated by the underlying Killarney batholith so that the small tonalite intrusions were not notably warmer than the rocks into which they were injected. The Long Lake diorite is thus older than the quartz-rich tonalite by an appreciable amount.

DIABASE AND GRANITE

The Keweenaw diabase is also older than the Killarney intrusives. The writer believes that both basic rock types belong to the same period of intrusion—a period somewhat earlier than that of the Killarney granite—and that the differences between diorite and diabase are largely due to metamorphism of the diorite intrusion by emanations from the Killarney batholith.

Both diorite and diabase are younger than Bruce sediments and older than the Killarney granite. This interval is an extensive period of time, however, and there may have been two periods of basic intrusion. The relation of the Sudbury norite to the granite may throw some light on the age relationships here. Collins has noted²⁰ that the Keweenaw diabase is widely distributed in the region between Lake Superior and the Ontario-Quebec boundary. He showed further that these rocks in the Cobalt and Gowganda areas²¹ varied regionally from a type of gabbroic composition at the north to one of noritic composition at the south, and therefore correlated the Sudbury norite lopolith with the diabase sills. He shows four masses of Killarney granite in contact with the south edge of the norite on

²⁰ *Ibid.*, p. 29.

²¹ *Op. cit.*, *Mem.* 143, p. 80.

his large map of the district.²² The relative ages of the granite and norite has been a controversial question ever since they have been studied. Granite intrudes norite at the Murray mine. Three miles southeast, at Copper Cliff, the norite has cooled against granite at No. 2 mine. A mile north, at Clarabelle Lake, granite intrudes the norite, as occurs also near the Creighton mine. The writer verified these facts in 1929 although they had been noted in the literature much earlier.²³

DIABASE AND DIORITE

Such a train of reasoning places the Keweenawan diabase very close in age to the Killarney batholithic intrusion, and it is possible that the intrusion of basic rocks marked the opening stage of igneous action in the region. If this is the case, then it would be quite probable that smaller masses, such as sills and their feeding dikes, would solidify much more rapidly than such a large mass as the Sudbury lopolith. The Long Lake diorite would also solidify more slowly than the sills, not only because of its greater mass, but also because the heat generated by the crushing and brecciation of the sediments during its emplacement would tend to prolong the period of crystallization. This longer period of crystallization would also allow more time for differentiation and assimilation, and it is quite possible that this accounts for the presence of primary hornblende instead of the pyroxene usual in the sills.

The Keweenawan diabase sills, east of Lake Panache and immediately south of this area, are metamorphosed by the Killarney granite to a type resembling the dioritic types common in other regions around the edges of batholiths.²⁴ The diabase on the north shore of Wright Lake is also altered to a type that megascopically resembles very closely the Long Lake diorite.

The writer believes, therefore, that the Long Lake diorite magma came from the same source as the diabase and that it differs from it in character because of a more protracted period of solidification during which assimilation and crystallization differentiation and

²² *Can. Geol. Surv.* (1929), Map 155A, Lake Huron Sheet, scale: 1 in. = 8 mi.

²³ A. E. Barlow, "The Nickel and Copper Deposits of the Sudbury Mining District," *Can. Geol. Surv. Ann. Rept.*, Vol. XIV, Part H (1901), p. 53.

²⁴ Quirke and Collins, *Op. cit.*, *Mem.* 160, p. 30.

especially emanations from a rising Killarney batholith were operative. The effects of assimilation and differentiation were more severe on the diorite than on the diabase probably because of its longer period of cooling and consequent higher temperatures. What is called the metamorphosed phase of the diorite owes its character to still further modification by emanations from the granite batholith. It should be added, however, that there is no absolute proof that the diorite was not a later intrusion than the diabase sills and dikes.

OLIVINE DIABASE

Olivine diabase dikes cut the Killarney granite at points outside the area and are, therefore, the youngest intrusive rocks in the region. They are usually assigned to a late Keweenawan age.

SEQUENCE OF INTRUSION

The writer's conception of the sequence of intrusion is as follows:

Basic magma was injected into the sediments of the Bruce series as they were being folded. Most of the sills and dikes did not undergo any very pronounced differentiation and solidified as Keweenawan diabase, but one mass differentiated to a somewhat greater degree and solidified as the Long Lake diorite.

A little later a large granitic batholith invaded the region and during its period of solidification the magma reacted extensively with the quartzite sediments, producing a border phase of quartz-rich tonalite. Emanations from the batholith also affected the Long Lake diorite, adding silica and soda to the rock, with the result that the diorite now grades into a more acidic phase, here called the "metamorphosed phase."

The writer agrees with Quirke and Collins who say that the source of the basic magma is not known, but is thought to have been different from that of the granitic magma, which was very probably derived from the melting of very deeply buried sediments of the Bruce series.²⁵

Dikes of olivine diabase were injected after the complete solidification of all of the other rocks.

²⁵ *Ibid.*, p. 98.

